

Yeosu dinosaur track sites of Korea: The youngest dinosaur track records in Asia

In Sung Paik^{a,*}, Min Huh^b, Kye Hun Park^a, Koo Geun Hwang^c, Kyung Sik Kim^d, Hyun Joo Kim^a

^a Department of Environmental Geosciences, Pukyong National University, Busan 608-737, South Korea

^b Faculty of Earth Systems and Environmental Science, Chonnam National University, Gwangju 500-757, South Korea

^c Korea Dinosaur Research Center, Chonnam National University, Gwangju 500-757, South Korea

^d Faculty of Biological Sciences, Chonbuk National University, Jeonju 561-756, South Korea

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Abstract

Eighty two dinosaur trackways were newly discovered in Upper Cretaceous lacustrine deposits on islands in the vicinity of Yeosu, Korea. Most dinosaur tracks occur in marginal lake deposits with polygonal desiccation cracks. The dinosaur tracks at the Yeosu site include 65 ornithopod trackways, 16 theropod trackways and one sauropod trackway. The prevalence of ornithopod tracks and the limited occurrence of sauropod tracks at the Yeosu site evidently reflect decreased sauropod diversity in the Upper Cretaceous. All ornithopod trackways represent bipeds, and most of the ornithopod tracks are similar to *Caririchnium* from other sites of the Korean peninsula. All fossil wood specimens collected in the study area represent conifers (three species of cupressaceous and two species of taxodiaceous conifers, and a new species) except for one, which is a discotyledon. It is thus inferred that the southwestern part of the Korean Peninsula was primarily covered with mesic forests with taxodiaceous trees during the Late Cretaceous. The K–Ar age of the Yeosu tracksite is determined as 81–65 Ma (Campanian to Maastrichtian). It indicates that the Yeosu track site contains the last records of dinosaurs living in Asia. Consequently, semi-arid palaeoclimatic conditions, together with a large lake as a persistent water source and rich vegetation of gymnosperm trees as food, resulted in the preservation of abundant dinosaur tracks in the Upper Cretaceous on the Korean Peninsula.

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1. Introduction

Although dinosaurs were exterminated at the end of the Cretaceous, the Upper Cretaceous, the Campanian and Maastrichtian in particular, are known from very rich dinosaur faunas (Weishampel, 1990; Dong, 1992; Lucas, 1999). In Asia, Late Cretaceous dinosaurs have been discovered in Mongolia and eastern China, but most of these remains are bones and eggs. In South Korea, by contrast, innumerable dinosaur tracks were found in the Upper Cretaceous (Turonian to Santonian) (Paik et al., 2001b), whereas bones are very rarely found. The Korean Peninsula is thus known as one of the most famous dinosaur track sites in the world. Recently, 82 dinosaur trackways are discovered in Upper Cretaceous lacustrine deposits on islands in the vicinity of Yeosu, Korea (Fig. 1).

Their geological ages are determined as Campanian and Maastrichtian. It is the youngest dinosaur track site in Asia. Recently, this site has been designated as a National Monument.

During the Late Cretaceous the paleoclimate of eastern Asia was very arid, and the Korean Peninsula climate was also semi-arid. However, there existed large lakes and gymnosperm trees that flourished on the Korean Peninsula during the Late Cretaceous. It is inferred that the presence of large lakes as persistent water sources and rich vegetation of gymnosperm trees as food might have supported dinosaurs on the Korean Peninsula. This finding thus provides additional evidence indicating that the Late Cretaceous, particularly the Campanian and Maastrichtian, was a flourishing time for dinosaurs, although they disappeared soon afterwards.

In this paper, the sedimentological features of the Yeosu dinosaur track-bearing deposits, the occurrence of dinosaur tracks, the taxonomy of petrified wood and the absolute

* Corresponding author. Fax: +82 51 628 6432.

E-mail address: paikis@pknu.ac.kr (I.S. Paik).

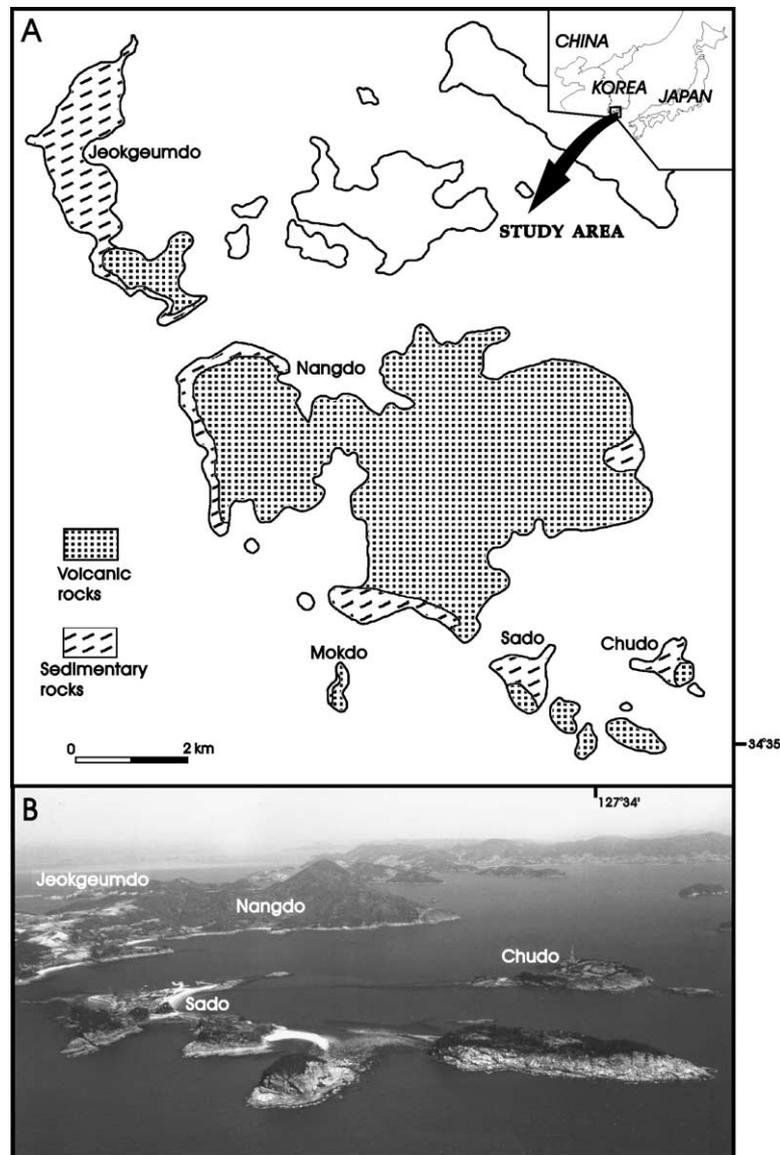


Fig. 1. Geological map (A) and overall view (B) of the study area.

geological ages are described. On the basis of these studies, the palaeobiological and geological significance of the Yeosu dinosaur track site is discussed.

2. Geological setting

A number of Cretaceous non-marine pull-apart basins, which were formed by northward subduction of the Izanagi Plate (Chough et al., 2000), are formed in South Korea. They consist of alluvial fan, fluvial plain, lacustrine deposits, and volcanic rocks. The Gyeongsang Basin is the largest, comprising a 9000-m-thick sequence of deposits assigned to the Gyeongsang Supergroup. It is divided into the Sindong, Hayang, and Yucheon groups, in ascending stratigraphical order (Chang, 1975). The Sindong and Hayang groups consist of an ascending sequence of alluvial fan, fluvial, and lacustrine deposits, respectively, whereas the Yucheon Group is

composed of volcanics, in addition to alluvial and lacustrine deposits (Um et al., 1983; Choi, 1985).

To the west of the Gyeongsang Basin, several subordinate basins, including the Haenam and Neungju basins, are present (Lee, 1999; Chough et al., 2000). They are filled with tuffs, lava flows, and epiclastic deposits. The frequent intercalation of volcanic rocks in both basins indicate that the sedimentary deposits of the Haenam and Neungju basins are time-correlated with the upper part of the Hayang Group to Yucheon Group in the Gyeongsang Basin. The absolute age of the Haenam Basin was determined as 96–78 Ma (Kim et al., 2003). The stratigraphic classification of sedimentary deposits at the Yeosu tracksite has not yet been established, and there are no stratigraphic names given to these deposits. However, the lithology of tuffs, lava flows, and epiclastic non-marine deposits implies that they are time-correlated with the Yucheon Supergroup of the Gyeongsang Basin. The sedimentary

deposits of the Yeosu area consist, in ascending order, of alluvial fan, fluvial plain, and lacustrine deposits.

The Yeosu site consists of five islands, including Jeokgeumdo, Nangdo, Mokdo, Chudo, and Sado (Fig. 1). The islands are composed of sedimentary rocks such as conglomerate, sandstone, and shale, as well as volcanic rocks of a wide compositional range (Fig. 1). Widespread Mesozoic igneous activity produced various plutons and volcanic eruptions, as reported from neighboring areas such as Goheung (Yun and Hwang, 1988; Park et al., 1997), Dolsan (Kim et al., 1994), Beolgyo (Kim and Park, 1996), and Guangyang–Seungju (Lee et al., 1992). These igneous rocks include various types intruded as sills or dykes and extruded lava flows or tuffs that cover older sedimentary rocks. Frequent igneous activity introduced a considerable amount of volcanogenic material in the sedimentary successions. Conglomerates contain volcanogenic materials up to boulder size. Diverse occurrences of igneous rocks offer a good opportunity to date the timing of sedimentation in the area.

Volcanic pebbles in the Jeokgeumdo conglomerate provide evidence for the first-stage of volcanic activity. Their composition ranges include basaltic andesite, andesite, basaltic trachyandesite, trachyandesite, and trachyte. It is peculiar that volcanic pebbles of rhyolitic composition have not been found in the Jeokgeumdo conglomerate, even though rhyolite flows and tuffs generally occur widely in the study area. This absence of rhyolite in the conglomerate suggests that the early-stage of volcanic activity was restricted to a relatively less

differentiated basic and intermediate composition. Later-stage volcanic activities are evidenced by the intrusion of intermediate to basic dykes, and the eruption of acidic to intermediate lava flows and tuffs related to the upper-level sedimentary deposits. The basaltic trachyandesite dyke of Chudo intrudes the dinosaur track-bearing deposits almost perpendicularly. A thick trachyandesitic flow overlies the Chudo sedimentary rocks almost conformably. The acidic to intermediate tuff overlies the dinosaur track-bearing deposits on Sado island.

3. Dinosaur track-bearing deposits

At the Yeosu tracksites, marginal to shallow lake deposits are extensively distributed throughout the islands. These lacustrine deposits consist of interlaminated to thinly interbedded fine-grained sandstone–siltstone–mudstone, planar- to cross-laminated sandstone–siltstone, tuffaceous sandstone, flaser- to lenticular-bedded fine-grained sandstone–mudstone, chert, marlstone, shales, and intraformational conglomerate (Fig. 2). Pyroclastic deposits including tuff and agglomerate and lava flow-rocks are intercalated in places.

Most dinosaur tracks occur in marginal lake deposits consisting of interlaminated to thinly interbedded, fine-grained sandstone–siltstone–mudstone. In these deposits, polygonal desiccation cracks are common (Fig. 3A) and some incomplete lenticular cracks are present in places (Fig. 3B). In cross section, the desiccation cracks show a ptygmatic shape due to compaction. Small-scale symmetrical and asymmetrical

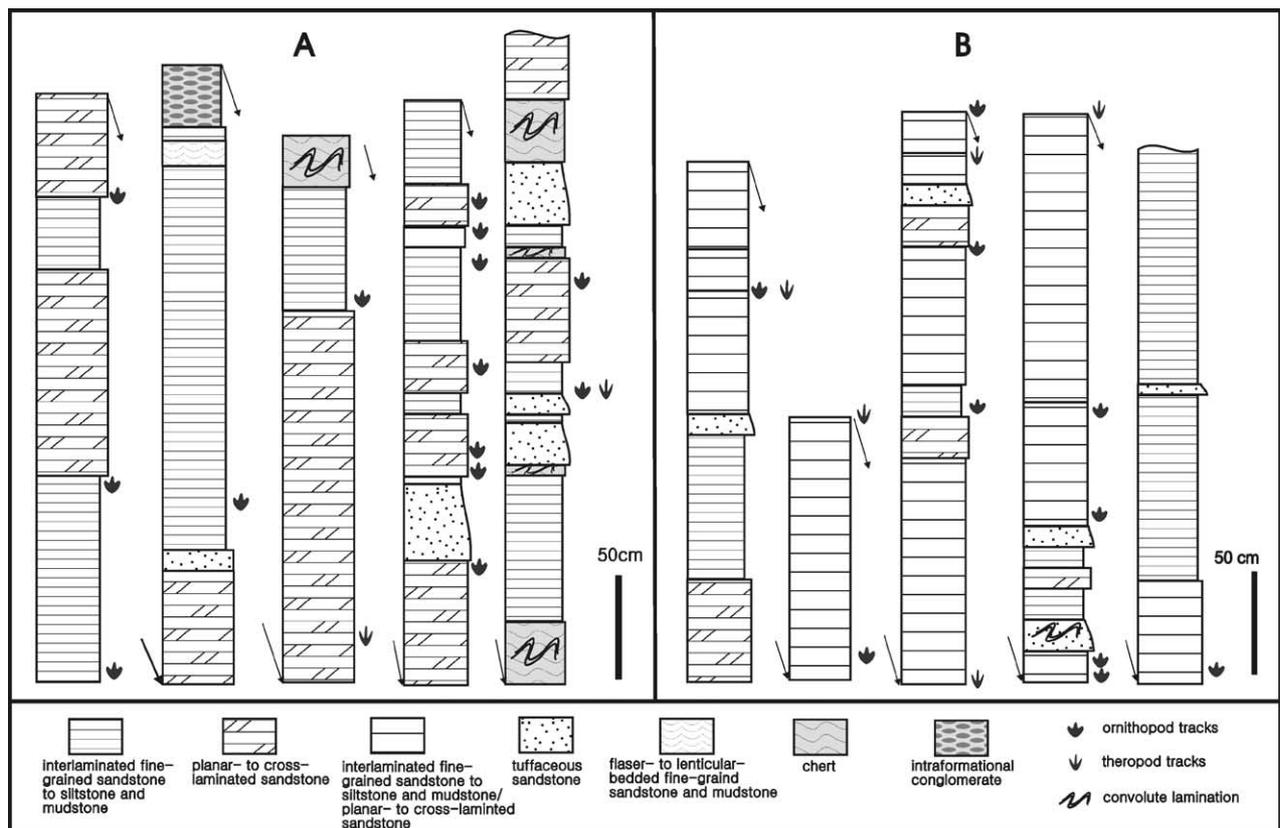


Fig. 2. Stratigraphic sections of dinosaur track-bearing deposits at Sado (A) and Chudo (B).

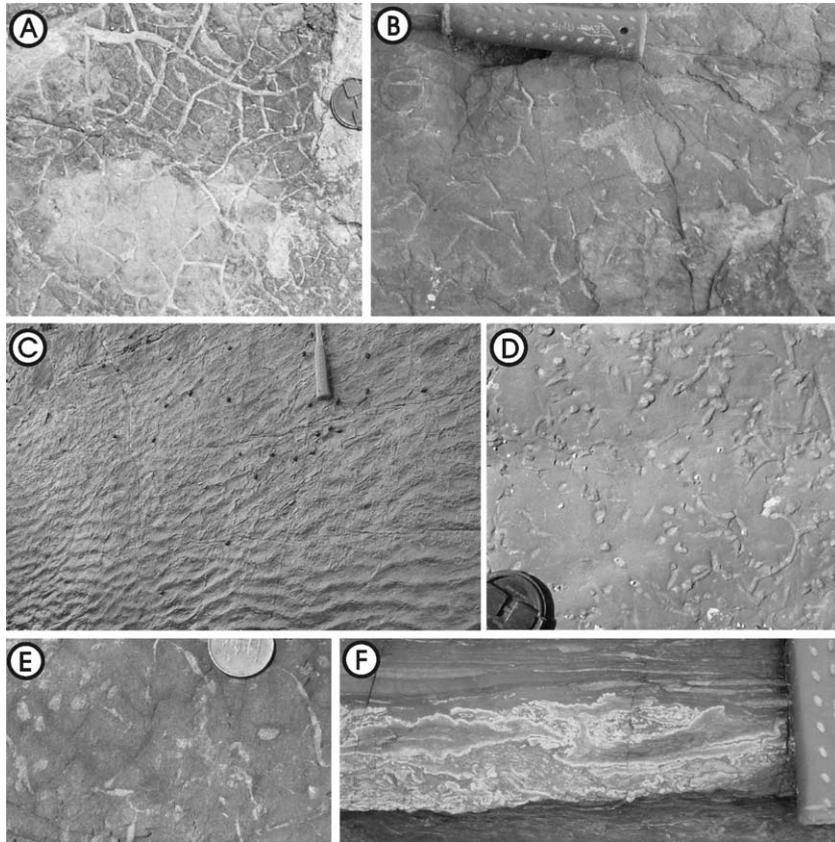


Fig. 3. Features of marginal lake deposits in the study area. (A) Polygonal desiccation cracks. (B) Subaerial lenticular cracks. (C) Sublinear wave ripples. (D) Trails and burrows. (E) Evaporite mineral casts associated with lenticular cracks. (F) Intraformational clasts of laminar calcrete.

ripples with sublinear crestlines are occasionally associated in these deposits (Fig. 3C), and rainprints are observed in places. Invertebrate burrows and trails are common (Fig. 3D). *Skolithos*-type burrows and circular resting marks (about 1 cm in diameter and a few mm deep) are observed. Evaporite mineral casts filled with sandstone (Paik and Kim, 1998) are present in the mudstone (Fig. 3E). In general, these deposits are calcareous and thin laminar calcrites formed in places. Clusters of calcispheres are associated with the laminar

calcretes. The laminar calcrites usually occur as intraformational chips (Fig. 3F).

The track-bearing marginal lake deposits usually alternate with shallow lake deposits composed of thin- to medium-bedded planar- to cross-laminated sandstone–siltstone with calcite cement. Ripple bedding is common and climbing ripples are observed in the shallow lake deposits (Fig. 4A). The upper parts of some ripples show convolute lamination due to deformation. Bidirectional cross-lamination is present in places

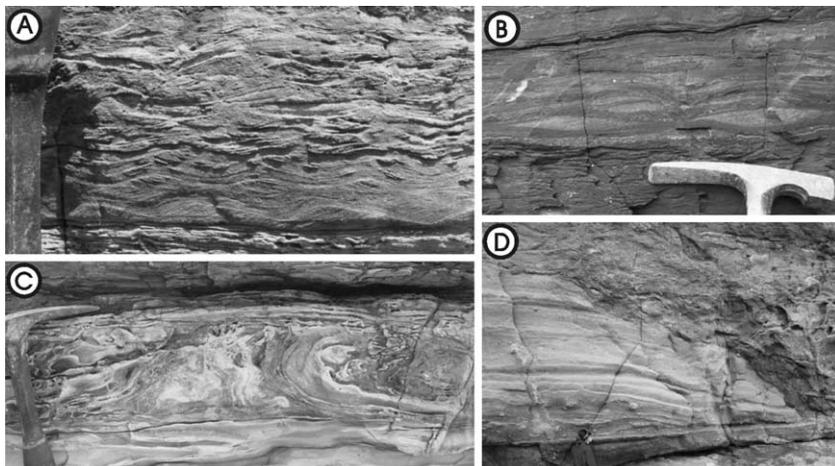


Fig. 4. Features of shallow lake deposits (A, B) and pyroclastic deposits (C, D) in the study area. (A) Climbing ripple bedding with bicurrential cross-lamination. (B) Flaser- to lenticular-bedding. (C) Convolute lamination in chert bed. (D) Cross-bedded pyroclastic surge deposits (arrow).

(Fig. 4A). The flaser- to lenticular-bedded fine-grained sandstone–siltstone–mudstone beds (Fig. 4B), which are typical in tidal deposits, are also associated with the marginal lake deposits. In places, marlstones containing ostracod carapaces are present. Intraformational conglomerates usually occur as shallow channel-fill deposits. Tuffaceous sandstones occur intermittently within these marginal to shallow lake deposits. They usually have erosional bases and show graded bedding. Chert also occurs intermittently as medium beds and convolute lamination is clearly observed (Fig. 4C), and deemed to have originated from tuffaceous deposits. Pyroclastic deposits are associated with the lacustrine deposits and consist of a pyroclastic flow and surge deposits (Fig. 4D). In the pyroclastic flow deposits, fragments of silicified or calcified wood occur and are usually subparallel to the bedding planes. In the surge deposits, large-scale cross-bedding is present.

Three types of rhythmic sedimentation are recognized in the sequences of the Yeosu tracksite. The first type is observed in interlaminated to thinly interbedded, fine-grained sandstone–siltstone–mudstone on a scale of lamination to thin-bedding. It indicates sheetflood deposition and subsequent desiccation and represents the seasonal alternation of wetting and drying periods. The second type is an alternation of marginal lake deposits and shallow lake deposits at thin- to thick-bed-scale (Fig. 5). It reflects an alternation of lake expansion and contraction due to short-term

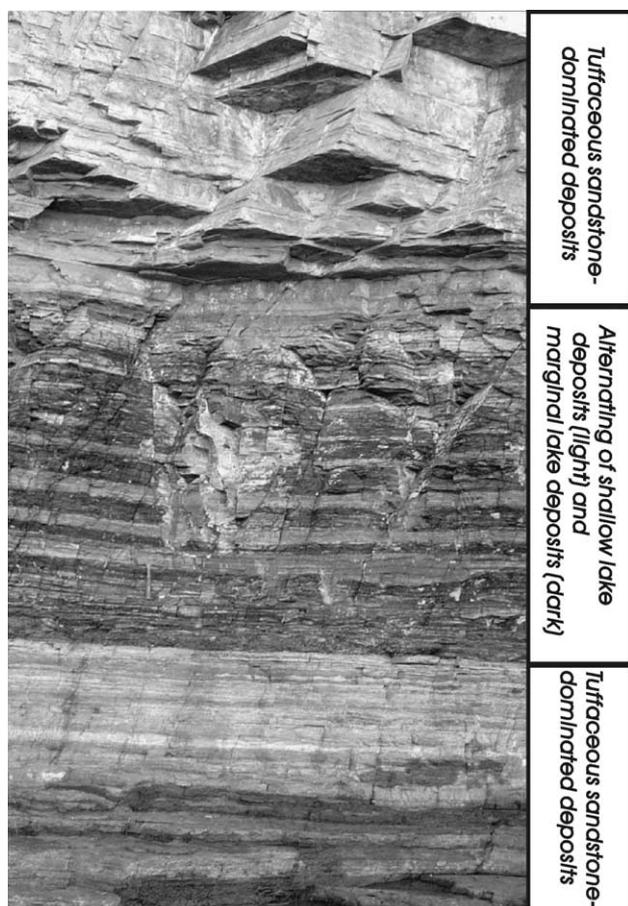


Fig. 5. Rhythmic sedimentation recognized in the Yeosu dinosaur track-bearing deposits.

climatic fluctuation. The third type is characterized by an alternation of stacked tuffaceous sandstone beds and epiclastic beds with intermittent intercalation of tuffaceous beds (Fig. 5). It occurs at meter-scale, and represents an alternation of active and inactive volcanic activities in the source area.

4. Dinosaur tracks

Dinosaur tracks at the Yeosu site are observed both on bedding surfaces and in cross-section exposures. All of the tracks observed on bedding surfaces form segments of discrete trackways. Dinoturbated deposits documented from the Upper Cretaceous Jindong Formation in Korea (Paik et al., 2001b) are not found at the Yeosu site. The footprints and trackways are recognized by the orientation of tridactyl or subcircular depressions on bedding surfaces, and some selective filling of sandstones in these depressions. In cross-section exposures, the tracks are recognized by asymmetrical depressions and syndepositional deformation as in the Jindong Formation (Paik et al., 2001b). These depressions have variable shapes depending on the angles of exposed profiles to the axis of the tracks (Fig. 6A–C). Some intensively deformed beds with syndepositional origin (Fig. 6D) are also deemed to be cross-sections of dinosaur bioturbation.

Eighty two trackways were found on the bedding surfaces at the Yeosu tracksite. They include 65 ornithopod trackways (Fig. 7), 16 theropod trackways (Fig. 8) and one indistinct sauropod trackway (Fig. 9). All of the ornithopod trackways represent bipeds like other Korean Cretaceous ornithopod tracks. Most of the ornithopod tracks from Yeosu are similar to *Caririchnium* or iguanodon-like tracks from the Dakota Group (Lockley, 1987). *Carririchnium* was originally defined as quadrupedal iguanodontian tracks (Leonardi, 1984). However, Lockley (1987) and Matsukawa et al. (1999) redefined it as quadrupedal or bipedal tracks from the Dakota Group. *Caririchnium* from Yeosu is similar to *Caririchnium protohadrosaurichnus* from the Cenomanian Woodbin Formation (Lee, 1997) and it differs from quadrupedal iguanodontian tracks of *Caririchnium leonardii*, (Leonardi, 1984). Yeosu ornithopod footprints also differ from *Hadrosaurichnoides* (Casanovas Cladellas et al. 1993) and *Hadrosauropus* (Lockley et al., 2003) by being less robust. Their morphology is compared to the North American *Amblydactylus* (Sternberg, 1932) as well as the European *Iguanodontipus* (Sarjeant et al., 1998).

There are two types of Yeosu theropod tracks. Footprints (Fig. 8A and C) with narrow, highly divergated digits are similar to *Irenesauripus* (Sternberg, 1932), while the slightly larger ones (Fig. 8B) are close to *Megalosauripus sensu* (Lockley et al., 1998). Various theropod tracks already have been found in the Upper Cretaceous Hwasun tracksite of Korea (Huh et al., 2003). Small theropod footprints from Yeosu are closely compared to *Magnoavipes caneeri* (Lockley et al., 2001).

The measurement of trackways at representative track sites are summarized in Tables 1–3. The dinosaur speeds are estimated using Alexander's formula (Alexander, 1976) based

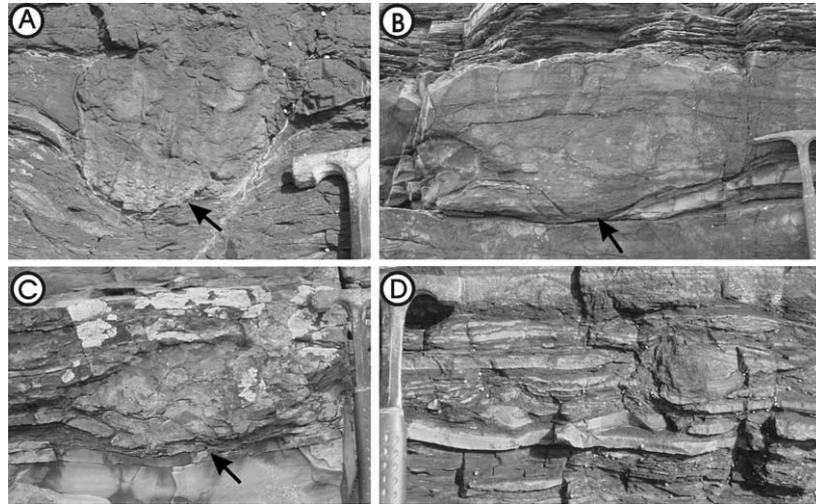


Fig. 6. Sectional views of dinosaur tracks observed in the study area as variably-shaped depressions. (A, B) Subvertical, deep depressions (arrows). (C) Low-angle and shallow depression (arrow). (D) Syndepositional folding presumed to be dinoturbation.

on the trackway parameters (stride and footlength). The main direction of the trackways shows two preferred orientations. One is apparently at a right angle to the paleoshoreline and the other is subparallel to the shoreline (Fig. 10).

5. Petrified wood

A total of 54 pieces of fossil wood were collected in the pyroclastic and tuffaceous deposits at the Yeosu site

(46 from Sado and 8 from Nangdo). All of them occur as fragments. No upright fossil trees were found, suggesting that they were transported from the hinterland. The polished transverse, tangential and radial thin sections were prepared using conventional techniques. For further anatomical identification, these microscopic slides were examined with a Zeiss Axiophot compound microscope. All of them are conifer trees, except for one, which is a discotyledon. However, the discotyledon is too poorly preserved to

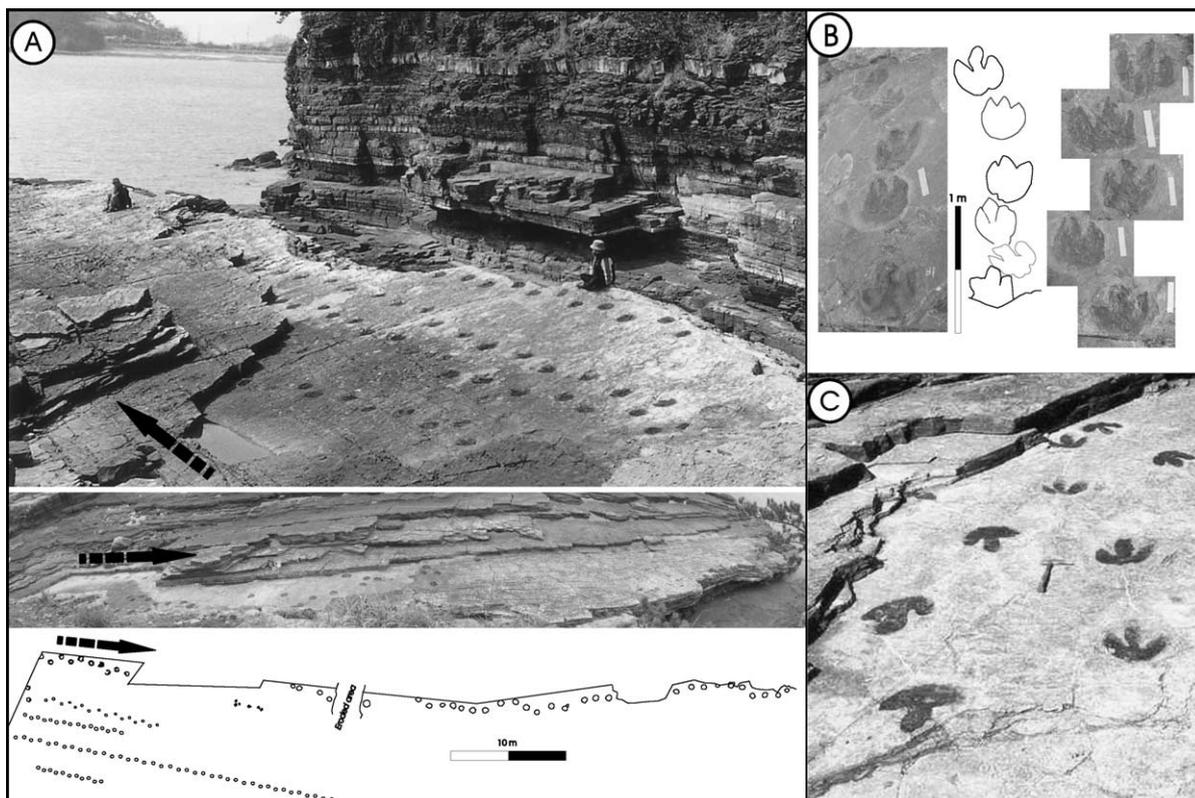


Fig. 7. Ornithopod trackways at Chudo (A) and Sado (B, C). Arrow in (A) indicates the same orientation for several trackways. (A) C6.1 in Table 2. (B) S3.3 in Table 1. (C) S8.1 in Table 1.

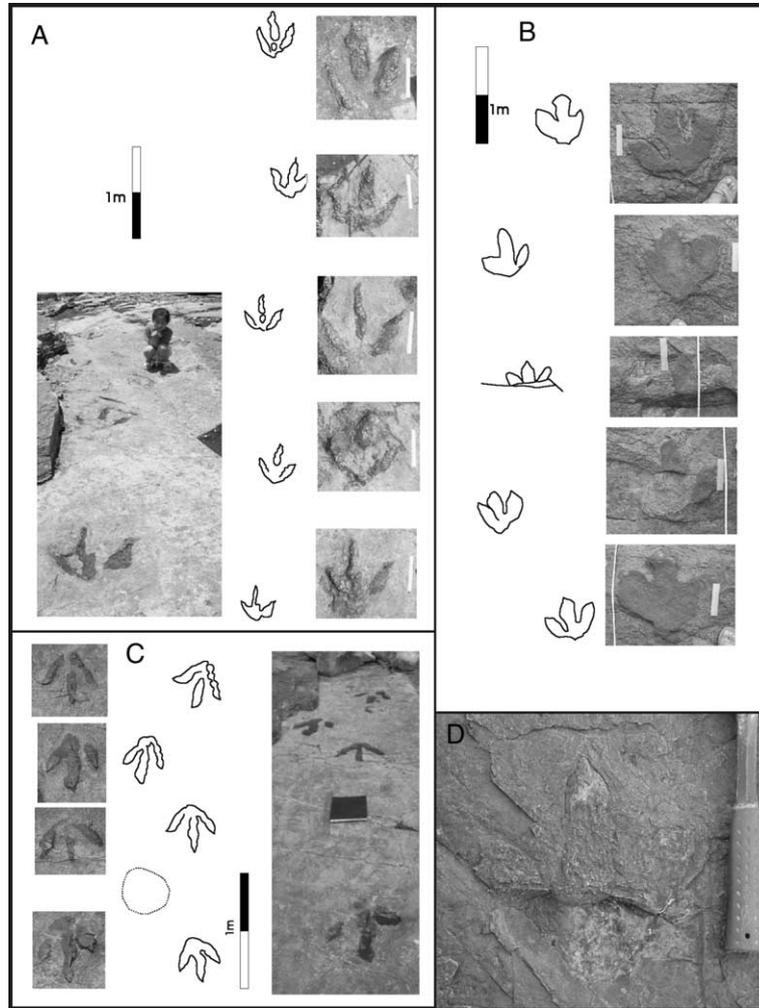


Fig. 8. Theropod trackways at Sado (A, B) and Nangdo (C). Claw impression is well preserved in one theropod track preserved at Sado (D). (A) S6.1 in Table 3. (B) N3.1 in Table 3. (C) S9.1 in Table 3.

identify its specific taxon. The conifers are classified into five taxa, viz., three species of cupressaceous (Figs. 11 and 12A–C) and two species of taxodiaceous conifers (Fig. 12D–F). All fossil wood and microscopic slides are stored in the Fossil Collection, Herbarium of Department of Biological Sciences, Chonbuk National University.

6. K–Ar analysis

K–Ar age determination was conducted on the volcanic rocks in order to bracket the formation ages of the dinosaur

Table 1
Measurements of ornithopod trackways from the track site at Sado

Trackway No.	Pes print length (cm)	Pes print width (cm)	Pes print depth (mm)	Pace length (m)	Stride length (m)	Hip height (m)	Stride length/hip height	Velocity (m/s)
S3.3	36.6	36.8	36	0.88	1.73	2.16	0.80	0.80
S3.5	35.6	32.8	63	0.86	1.68	2.10	0.80	0.78
S3.6	35.2	31.7	68	0.90	1.79	2.07	0.86	0.88
S3.7	35.8	31.1	40	0.74	1.45	2.10	0.69	0.61
S3.8	42.5	40.9	62	0.97	1.94	2.51	0.77	0.81
S3.9	39.2	38.4	68	0.94	1.85	2.32	0.80	0.82
S3.10	28.3	29.9	42	0.64	1.29	1.67	0.77	0.65
S3.11	27.6	26.0	49	0.64	1.28	1.63	0.79	0.67
S3.12	34.8	32.7	24	0.75	1.54	2.06	0.75	0.69
S8.1	31.3	31.0	21	0.89	1.85	1.85	1.00	1.07
Average	34.7	33.1	47	0.82	1.64	2.05	0.80	0.78

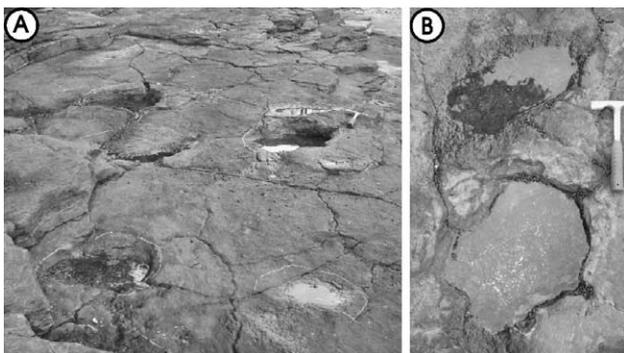


Fig. 9. Indistinctly preserved sauropod trackways at Sado. (A) Overall view. (B) One of manus-pes set in (B).

Table 2
Measurements of ornithopod trackways from the track site at Nangdo and Chudo

Trackway No.	Pes print length (cm)	Pes print width (cm)	Pes print depth (mm)	Pace length (m)	Stride length (m)	Hip height (m)	Stride length/hip height	Velocity (m/s)
N12.2	36.2	36.1	30.8	1.01	2.04	2.14	0.96	1.06
N12.3	33.8	31.2	48.0	?	2.04	1.99	1.02	1.15
N12.5	31.5	36.7	26.6	1.08	2.03	1.86	1.09	1.23
N12.6	27.0	33.4	32.4	0.72	1.52	1.59	0.95	0.91
N12.7	31.5	30.0	23.6	0.91	1.74	1.86	0.93	0.95
N12.8	26.5	28.6	5.1	0.80	1.58	1.56	1.01	1.00
C6.1	41.5	38.3	25.0	0.94	1.71	2.45	0.70	0.68

Table 3
Measurements of theropod trackways from Sado and Nangdo

Trackway No.	Pes print length (cm)	Pes print width (cm)	Pes print depth (mm)	Pace length (m)	Stride length (m)	Hip height (m)	Stride length/hip height	Velocity (m/s)
S2.1	27.6	29.0	18	1.03	2.08	1.63	1.3	1.50
S6.1	41.5	38.5	25	1.54	3.08	2.04	1.5	2.23
S9.1	36.5	36.3	25	1.06	1.72	1.79	1.0	0.98
N2.2	27.5	25.0	17	0.61	1.93	1.35	1.4	1.65
N2.3	22.8	23.0	29	1.11	1.91	1.02	1.9	2.24
N3.1	46.9	46.8	?	1.40	2.65	2.30	1.2	1.50

track-bearing sedimentary deposits of the study area. Representative samples were cut to make slabs about 5 mm thick. Weathered and altered portions were removed. Saw-marks were also removed using sandpaper. After crushing in a samples by tungsten carbide jaw crusher, fractions collected between sieves with 150–250 μm opening size were collected for age determination. Such fraction samples were washed with deionized water and then dried at 60 $^{\circ}\text{C}$ in the oven. K and Ar

abundances were determined at the Korea Basic Science Institute using an atomic absorption spectrometer and static vacuum mass spectrometer (VG 5400), respectively. All ages in this paper are reported with a 1σ error.

Dated volcanic rocks give approximately a 30 My span of K–Ar ages (Table 4). The oldest ones are the volcanic pebbles in the Jeokgeumdo conglomerate, which is the lowermost sedimentary bed of this area. Three volcanic pebbles of trachyandesite, trachyte, and basaltic trachyandesite have K–Ar ages of 91.8 ± 3.5 , 80.8 ± 3.1 , and 81.1 ± 1.6 Ma, respectively. Therefore, sedimentation at the Yeosu site occurred after ca. 81 Ma at maximum.

A slightly younger age of 77.0 ± 2.3 Ma is recorded by a dyke on Chudo island that cuts the dinosaur track-bearing deposits almost perpendicularly. Therefore, the age of this dyke provides a minimum sedimentation age for the Chudo sedimentary deposits. However, a trachyandesite flow on Chudo shows a much younger age of 71.1 ± 1.4 Ma. Most of the volcanic rocks from the other islands reveal similar to slightly younger ages of 73–65 Ma. A rhyolite flow from Jangsado is dated at 72.9 ± 1.4 Ma. A volcanic pebble in the Mokdo conglomerate yields an age of 72.4 ± 1.5 Ma which agrees well with the age obtained from the pyroclastic sedimentary rock (73.7 ± 1.5 Ma) underlying the deposits on this island. Such agreement reveals that the sedimentary rocks of Mokdo are younger than Chudo sedimentary deposits and have a maximum age of deposition at about 74 Ma. Slightly younger ages are recorded by the near perpendicular dikes of Mokdo and Sado (Siruseom), which are 69.6 ± 1.4 and 68.1 ± 1.6 Ma, respectively. Volcanic breccias in the tuffs of Sado (Jungdo and Siruseom) record similar ages (67.8 ± 1.6 – 65.5 ± 1.3 Ma). Such late stage volcanic rocks underlie the Sado dinosaur-track bearing deposits and, therefore, the minimum depositional age of this deposit is at least 65 Ma.

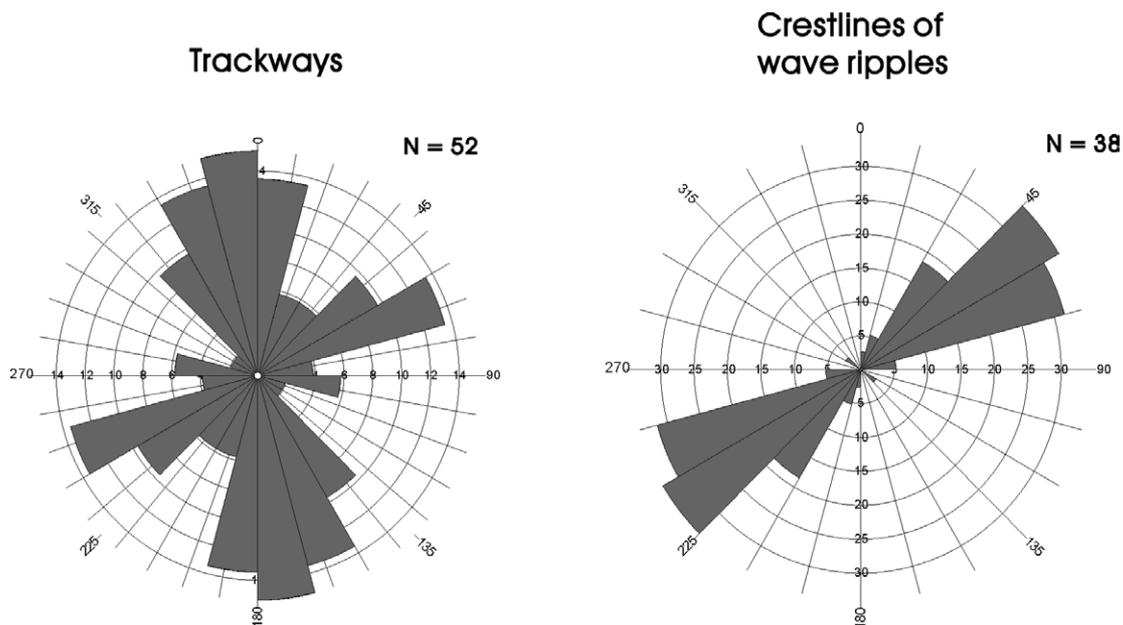


Fig. 10. Orientations of dinosaur trackways and ripple crestlines in the study area.

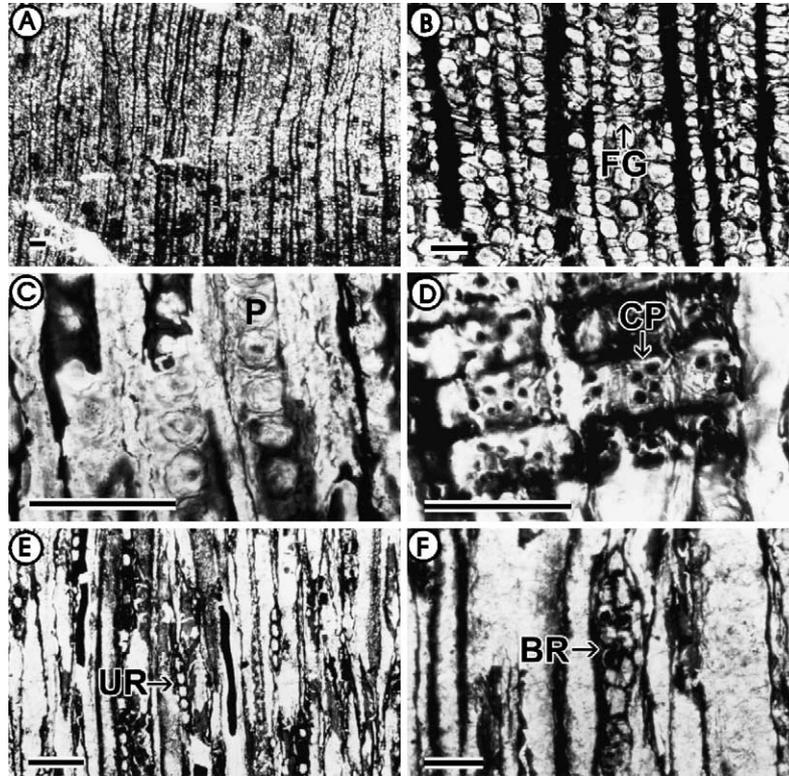


Fig. 11. Thin section photomicrographs of *Cupressinoxylon* sp. Scale bars are 100 μm. (A, B) Transverse section showing faint growth rings (FG). (C) Radial section showing bordered pits (P) on radial wall of tracheids. (D) Magnified radial section showing cross field pits (CF). (E) Tangential section showing uniseriate rays (UR). (F) Magnified tangential section showing partly biseriate ray (BR).

7. Discussion

As previously mentioned, numerous sites with dinosaur tracks and a few with dinosaur bones and eggs have been found in Cretaceous non-marine sedimentary basins in Korea. The dinosaur tracks occur mostly in Upper Cretaceous marginal lake deposits, whereas the dinosaur bones were found mostly in

the Lower Cretaceous flood-plain deposits. Most dinosaur eggs are present in the Upper Cretaceous alluvial fan deposits. Regardless of fossil types, most dinosaur remains are preserved in arid palaeosols (Paik et al., 2001a,b, 2003a,b, 2004). On the basis of these occurrences, it is considered that dinosaurs inhabited a semiarid alluvial fan, fluvial plain, and lake margins on the Korean Peninsula throughout the Cretaceous

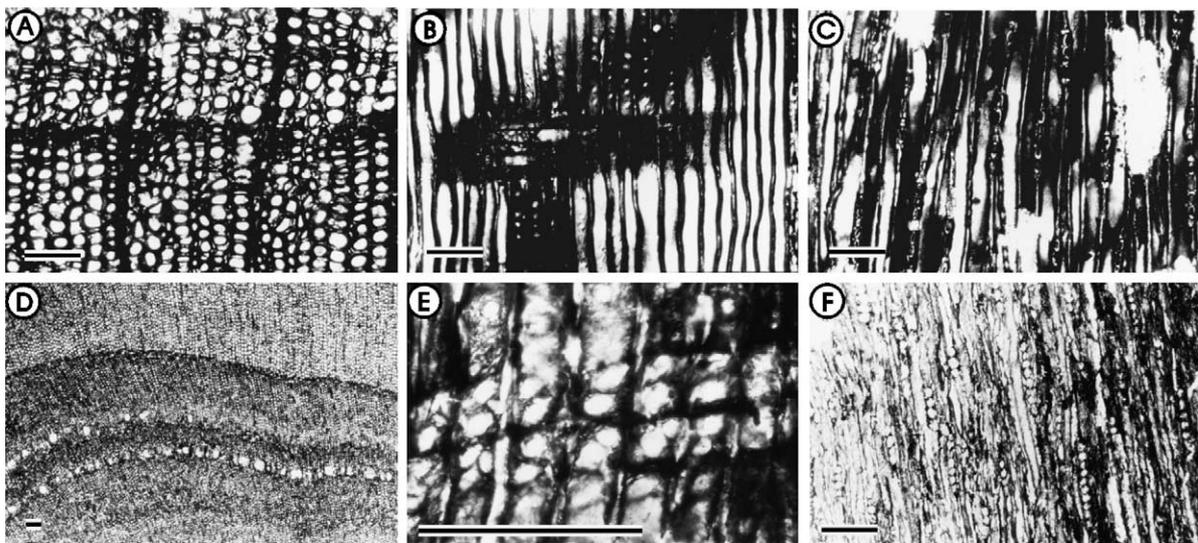


Fig. 12. Thin section photomicrographs of *Cupressinoxylon vectense* (A–C) and *Taxodioxyylon nihongii* (D–F). Scale bars are 100 μm. (A) Transverse section showing growth ring. (B) Radial section showing bordered pits on radial wall of tracheids. (C) Tangential section showing uniseriate rays. (D) Transverse section showing growth rings. (E) Radial section showing taxodioid cross field pits. (F) Tangential section showing uniseriate rays.

Table 4
K–Ar ages measured from various volcanic and volcanoclastic sedimentary rocks

Sample	Type	K (wt%)	wt (g)	radiogenic ^{40}Ar (10^{-8}ccSTP/g)	Error (1σ)	^{36}Ar (10^{-10}ccSTP/g)	error (1σ)	Age (Ma)	error (1σ)	Air (%)	
Chudo	C-1	dyke	1.311	0.02069	400.4	9.2	35.2	2.5	77.0	2.3	20.6
	C-3	lava flow	2.134	0.02002	600.6	1.8	105.8	0.5	71.1	1.4	34.2
Sado	S-2	vol. breccia	1.452	0.01869	375.9	1.6	62.3	0.4	65.5	1.3	32.9
	S-4	vol. breccia	1.679	0.01812	450.4	6.2	168.1	1.1	67.8	1.6	52.5
	S-7	dyke	0.670	0.01635	180.7	2.3	42.2	0.5	68.2	1.6	40.8
	JU-1	tuff	1.936	0.01589	517.0	1.8	32.7	0.3	67.5	1.3	15.7
	JA-1-2	tuff	2.687	0.01525	775.8	1.6	29.8	0.4	72.9	1.4	10.2
Mokdo	M-2	pyrocl. rock	1.292	0.01710	377.0	1.7	24.1	0.4	73.7	1.5	15.9
	M-3	dyke	1.088	0.01924	299.6	1.2	20.7	0.3	69.6	1.4	17.0
	M-7	vol. pebble	1.318	0.01761	378.2	2.9	23.9	0.2	72.4	1.5	15.7
Jeok-geumdo	JE-2-2	vol. pebble	0.075	0.01925	27.4	0.9	18.5	0.2	91.8	3.5	66.6
	JE-2-4	vol. pebble	0.112	0.02125	35.9	1.2	16.1	0.2	80.8	3.1	56.9
	JE-2-6	vol. pebble	1.120	0.02116	360.6	1.3	18.9	0.3	81.1	1.6	13.4

under a semi-arid climate. The semi-arid palaeoclimates of the Cretaceous basins of Korea are attributed to rain shadow effects of the surrounding mountains (Paik et al., 2003a,b).

Twenty seven localities of dinosaur tracks have been discovered from the Cretaceous in Korea. Ornithopod tracks are the most abundant in all Korean tracksites, and sauropod tracks are subordinate (Lim et al., 1994; Huh et al., 2003). Theropod track occurrences are very limited. Most of the dinosaur tracks in Korea are preserved in interlaminated fine-grained sandstones and siltstone–mudstone deposits, which were deposited on the dry mudflats of a lake margin by sheetfloods, and partially transformed into arid palaeosols (Paik et al., 2002, Paik and Kim (2003)). Paik et al. (2001a) suggested that repeated deposition by sheetfloods on the mudflats adjacent to a perennial lake, which was a persistent water source during droughts, and the subsequent hardening by calcareous pedogenesis, were the main reasons for the extensive preservation of dinosaur tracks in the Upper Cretaceous deposits of Korea. The sedimentological features of the Yeosu track-bearing deposits also indicate that palaeoenvironmental and preservational conditions are similar to those of other Upper Cretaceous dinosaur track-bearing deposits in Korea. The predominance of subperpendicular directions of the Yeosu dinosaur trackways to paleoshorelines suggests that dinosaurs used the lake as a persistent water source during droughts. The intercalations of pyroclastic and tuffaceous deposits indicate intermittent volcanic activity.

The geological ages of the Yeosu track deposits are assigned to the Campanian to Maastrichtian based on K–Ar absolute age measurements of intercalated tuffs, pyroclastic conglomerates, and dykes. Although many dinosaur fossils have been discovered in the Upper Cretaceous of Asia, Asian records of Upper Cretaceous dinosaur tracks are very limited (Weishampel, 1990). In China, dinosaur tracks have been found at several localities, but the youngest track site in China is Santonian (Zhen et al., 1989; Lockley et al., 2002). Dinosaur tracks were also discovered in Japan, but they are from the Early Cretaceous (Matsukawa et al.,

1995). Therefore, the Yeosu dinosaur tracksites are the last record of dinosaur activity in Asia.

There are several Upper Cretaceous dinosaur tracksites such as in Denton County, Texas (Lee, 1997), Dinosaur Ridge near Denver, Colorado (Lockley et al., 2001), sites in northern New Mexico (Lockley and Hunt, 1995), the Lisbon region of Portugal and the Felonega site on the Istrian peninsula (Lockley and Meyer, 2000). At these track sites, theropod and ornithopod tracks prevail, but the sauropod tracks are very limited. In general, sauropod tracks are also rare at Upper Cretaceous dinosaur tracksites in Korea, including Haenam and Hwasun (Huh et al., 2003) and the present study area, although various sauropod tracks occur in the Upper Cretaceous Jindong Formation (Lim et al., 1989; Lockley and Hunt, 1994; Hwang et al., 2002; Huh et al., 2003). The prevalence of ornithopod tracks and the limited occurrence of sauropod tracks at the Yeosu site appear to correspond with a local or regional decrease in sauropod abundance and/or diversity during the Late Cretaceous (Weishampel, 1990; Lucas, 1999).

The very limited occurrence of angiosperm trees at the Yeosu dinosaur track site is unusual, compared with the abundance of angiosperm trees in the Upper Cretaceous of Japan (Stopes and Fujii, 1910; Shimakura, 1937; Takahashi and Suzuki, 2003). The fossil wood from other Upper Cretaceous deposits in Korea are all gymnosperm trees including *Cupressinoxylon* and *Taxodioxylon* (Kim et al., 2002). The genera *Cupressinoxylon* and *Taxodioxylon* have usually been considered as interrelated taxa and their affinities are compared with extant *Sequoia* (Ogura, 1944; Suzuki and Watari, 1994). The genus *Sequoia* inhabits mesic forests in a temperate climate. It is thus supposed that the southwestern part of the Korean Peninsula was primarily covered with mesic forests with taxodiaceous trees during the Late Cretaceous.

Consequently, it is inferred that the presence of large lakes as persistent water sources and rich vegetation of gymnosperm trees as food evidently sustained dinosaurs on the Korean Peninsula during the Late Cretaceous. In addition to these settings, a semi-arid palaeoclimatic condition might have

resulted in the preservation of abundant dinosaur tracks in Upper Cretaceous rocks of Korea.

8. Conclusions

1. The dinosaur track-bearing deposits at Yeosu formed around lake margins with repeated sheetflood deposition, while volcanic activity took place intermittently in the vicinity of the track site.
2. The geological age of the Yeosu dinosaur tracksite is estimated, by K–Ar dating, as Campanian to Maastrichtian. It is the last record of dinosaur activity in Asia.
3. The prevalence of ornithopod tracks and the very limited occurrence of sauropod tracks at the Yeosu sites evidently corresponds with a local or regional decrease of sauropod abundance and/or diversity in the Late Cretaceous.
4. The southwestern part of the Korean Peninsula was primarily covered with mesic forests with taxodiaceous trees during the Late Cretaceous.
5. A semi-arid palaeoclimate, together with the presence of large lakes as persistent water sources and a rich vegetation of gymnosperm trees as food on the Korean Peninsula during the Later Cretaceous resulted in the accumulation and preservation of abundant dinosaur tracks.

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References

- Alexander, R. McN., 1976. Estimates of speeds of dinosaurs. *Nature* 261, 129–130.
- Casanovas Cladellas, M.L., Ezquerro Miguel, R., Fernández Ortega, A., Perez-Lorente, F., Santafé Llopis, Y.V., Torcida Fernández, F., 1993. Tracks of a herd of webbed ornithopods and other footprints found in the same site (Igea, La Rioja, Spain). *Revue de Paléobiologie Spécial* 7, 29–36.
- Chang, K.H., 1975. Cretaceous stratigraphy of southeast Korea. *J. Geol. Soc. Korea* 11, 1–23.
- Choi, H.I., 1985. Sedimentology and its implication for stratigraphic classifications of the cretaceous gyeongsang Basin. *J. Geol. Soc. Korea* 21, 26–37.
- Chough, S.K., Kwon, S.T., Lee, J.H., Choi, D.K., 2000. Tectonic and sedimentary evolution of the Korean peninsula: a review and new view. *Earth-Sci. Rev.* 52, 175–235.
- Dong, Z., 1992. *Dinosaurian Faunas of China*. China Ocean Press, Beijing, 188 pp.
- Huh, M., Hwang, K., Paik, I.S., Chung, C.H., 2003. Dinosaur tracks from the Cretaceous of South Korea: distribution, occurrence and paleobiological significance. *Island Arc* 12, 132–144.
- Hwang, K.G., Huh, M., Paik, I.S., 2002. Sauropod tracks from the Cretaceous Jindong formation, Hogyeri, Masan-city. *J. Geol. Soc. Korea* 38, 75–361.
- Kim, C.B., Park, Y.S., 1996. The petrochemistry and geochronology of plutonic rocks in the Beolkyo area, Chonnam. *J. Korean Earth Sci. Soc.* 17, 227–240.
- Kim, H.N., Shin, I.H., Ahn, K.S., 1994. Lithochemical features of granite mass and their relation to mineralization in the Dolsan area. *J. Korean Earth Sci. Soc.* 115, 439–451.
- Kim, K.S., Jeong, E.K., Suzuki, M., Huh, M., Paik, I.S., 2002. Some coniferous fossil woods from the Cretaceous of Korea. *Geosci. J.* 6, 141–148.
- Kim, C.B., Huh, M., Cheong, C.S., Lockley, M., Chang, H.W., 2003. Age of the pterosaur and web-footed bird tracks associated with dinosaur footprints from South Korea. *Island Arc* 12, 125–131.
- Lee, Y.N., 1997. Bird and dinosaur footprints in the Woodbine formation (Cenomanian), Texas. *Cretaceous Res.* 18, 64–849.
- Lee, D.W., 1999. Strike-slip fault tectonics and basin formation during the Cretaceous in the Korean Peninsula. *Island Arc* 8, 31–218.
- Lee, C.S., Kim, Y.J., Park, C.Y., Lee, C.J., 1992. Geochemistry of granitoids in the Kwangyang-Seungju area. *J. Korean Inst. Miner. Geol.* 25, 51–60.
- Leonardi, G., 1984. Le impronte di dinosauri. In: Bonaparte, J.F., et al. (Eds.), *Sulle Orme dei Dinosauri* Errizo, Venezia, pp. 165–186.
- Lim, S.K., Yang, S.Y., Lockley, M.G., 1989. Large dinosaur footprint assemblages from the Cretaceous Jindong Formation of Southern Korea. In: Gillette, D.D., Lockley, M.G. (Eds.), *Dinosaur Tracks and Trace*. Cambridge University Press, New York, pp. 333–336.
- Lim, S.K., Lockley, M.G., Yang, S.Y., Fleming, R.F., Houck, K., 1994. A preliminary report on sauropod tracksites from the Cretaceous of Korea. *Gaia: Revista de Geociencias, Museu Nacional de Historia Natural* 10, 109–117.
- Lockley, M.G., 1987. Dinosaur trackways. In: Czerbas, Olsen, S.J. (Eds.), *Dinosaurs Past and Present*, Los Angeles Country Museum Symposium, pp. 80–95.
- Lockley, M.G., Hunt, A.P., 1994. A track of the giant theropod dinosaur *Tyrannosaurus* from close to the Cretaceous/Tertiary boundary, northern New Mexico. *Ichnos* 3, 213–218.
- Lockley, M.G., Hunt, A.P., 1995. *Dinosaur Tracks and Other Fossil Footprints of the Western United States*. Columbia University Press, New York, 338 pp.
- Lockley, M.G., Meyer, C.A., 2000. *Dinosaur Tracks and Other Fossil Footprints of Europe*. Columbia University Press, New York, 323 pp.
- Lockley, M.G., Meyer, C.A., dos Santos, V.F., 1998. Megalosaurus and the problematic concept of megalosaur footprints. *Gaia* 15, 313–337.
- Lockley, M.G., Wright, J.L., Matsukawa, M., 2001. A new look at *Magnavipes* and so-called ‘Big Bird’ tracks from Dinosaur ridge (Cretaceous, Colorado). *Mountain Geologist* 38, 46–137.
- Lockley, M.G., Wright, J., White, D., Matsukawa, M., Jianjun, L., Lu, F., Hong, L., 2002. The first sauropod trackways from China. *Cretaceous Res.* 23, 363–381.
- Lockley, M.G., Nadon, G., Currie, P., 2003. A diverse dinosaur-bird footprint assemblage from the Lance formation, Upper Cretaceous, Eastern Wyoming: Implications for Ichnotaxonomy. *Ichnos* 11, 229–249.
- Lucas, S.G., 1999. *Dinosaurs*. McGraw-Hill, New York, 278 pp.
- Matsukawa, M., Futakami, M., Lockley, M.G., Chen, P., Chen, J., Cao, Z., Bolotsky, U.L., 1995. Dinosaur footprints from the lower cretaceous of eastern Manchuria, northeastern China: implications for the recognition of an ornithopod ichnofacies in east Asia. *Palaio* 10, 3–15.
- Matsukawa, M., Lockley, M.G., Hunt, A.P., 1999. Three age group of ornithopods inferred from footprints in the mid-Eretaceous Dakoda Group, eastern Colorado, North America. *Palaeogeog. Palaeoclimatol. Palaeoecol.* 147, 39–51.
- Ogura, Y., 1944. Notes on fossil woods from Japan and Manchoukuo. *Jpn. J. Bot.* 8, 345–365.
- Paik, I.S., Kim, H.J., 1998. Subaerial lenticular cracks in Cretaceous lacustrine deposits, Korea. *J. Sediment. Res.* 68, 80–87.
- Paik, I.S., Kim, H.J., 2003. Palustrine calcretes of the Cretaceous Gyeongsang supergroup, Korea: variation and paleoenvironmental implications. *Island Arc* 12, 110–124.
- Paik, I.S., Kim, H.J., Lee, Y.I., 2001a. Dinosaur track-bearing deposits in the Cretaceous Jindong formation, Korea: occurrence, palaeoenvironments and preservation. *Cretaceous Res.* 22, 79–92.

- Paik, I.S., Kim, H.J., Park, K.H., Song, Y.S., Lee, Y.I., Hwang, J.Y., Huh, M., 2001b. Palaeoenvironments and taphonomic preservation of dinosaur bone-bearing deposits in the lower Cretaceous Hasandong formation, Korea. *Cretaceous Res.* 22, 627–642.
- Paik, I.S., Kim, H.J., Huh, M., 2002. Cretaceous dinosaur deposits of Korean peninsula: stratigraphy, paleoenvironments, and taphonomic preservation. Fourth International Symposium of IGCP 434, Khabarovsk, 87a.
- Paik, I.S., Kim, H.J., Ahn, G.Y., 2003. Preliminary study on the Cretaceous saline lake records of Korea. Proceeding Third International Limnogeology Congress, Tucson, 205 pp.
- Paik, I.S., Kim, H.J., Huh, M., Park, K.H., 2003b. Dinosaur deposits of Korea: stratigraphy, paleoenvironments, and preservation. *J. Vert. Paleontol.* 23 (Suppl. 3), 85A.
- Paik, I.S., Huh, M., Kim, H.J., 2004. Dinosaur egg-bearing deposits (upper Cretaceous) of Boseong, Korea: occurrence, palaeoenvironments, taphonomy, and preservation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 205, 155–168.
- Park, Y.S., Kim, C.B., Yoon, C.H., Ahn, K.S., 1997. The petrochemistry and geochronology of Cretaceous plutonic rocks in the Koheung area, Chonnam. *J. Korean Earth Sci. Soc.* 18, 70–83.
- Sarjeant, W.A.S., Delair, Y.B., Lockley, M.G., 1998. The footprints of *Iguanodon*: a history and taxonomic study. *Ichnos* 6, 183–202.
- Shimakura, M., 1937. Studies on fossil woods from Japan and adjacent lands. Contribution II. The Science Report of the Tohoku Imperial University Section Series 19, pp. 1–73.
- Sternberg, C.M., 1932. Dinosaur tracks from Peace River, Birtish Columbia. National Museum of Canada, Annual Report (1930), pp. 59–85.
- Stopes, M.C., Fujii, K., 1910. Studies on the structure and affinities of crataceous plants. *Philos. Trans. R. Soc. Lond. Ser. B CCI*, 27–70.
- Suzuki, M., Watari, S., 1994. Fossil wood flora of the early Miocene Nawamata formation of Monzen, Noto Peninsula, Central Japan. *J. Plant Res.* 107, 63–76.
- Takahashi, K., Suzuki, M., 2003. Dicotyledonous fossil wood flora and early evolution of wood characters in the Cretaceous of Hokkaido, Japan. *IAWA J.* 24, 269–309.
- Um, S.H., Choi, H.I., Son, J.D., Oh, J.H., Kwak, Y.H., Shin, S.C., Yun, H.S., 1983. Geological and geochemical studies on the Gyeongsang Supergroup in the Gyeongsang Basin, Korea. *Inst. Energy and Resources Bull.* 36. Korea Institute of Energy and Resources, Deajeon.
- Weishampel, D.B., 1990. In: Weishampel, D.B. (Ed.), *The Dinosauria*, University of California Press, Berkeley, CA, pp. 63–139.
- Yun, S.H., Hwang, I.H., 1988. Volcano-stratigraphy and petrology of the volcanic mass in the Koheung Peninsula, South Cheolla Province, Korea. *J. Korean Inst. Min. Geol.* 21, 335–348.
- Zhen, S., Li, R., Rao, C., Mateer, N., Lockley, M.G., 1989. A review of dinosaur footprint in China. In: Gillette, D.D., Lockley, M.G. (Eds.), *Dinosaurs Past and Present*. Cambridge University Press, Cambridge, pp. 187–197.